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Some Are Born With White Space, Some Achieve White Space, And Some Have White Space Thrust Upon Them

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Abstract—A few steps from Shakespeare's spiritual home The Globe Theatre in London, the UK regulator Ofcom is formulating its own well-crafted play based on TV White Spaces (TVWS). Such work comfortably fits into the Shakespearean analogy of “some achieve white space” through implementation of clever twists to make white space available while not causing harmful interference to incumbents, noting that the UK is extremely busy in terms of spectrum usage. This paper reports on some of the work of by our trial within the Ofcom TV White Spaces Pilot, building key observations on beneficial usage scenarios for TVWS through link testing examples. It also particularly investigates performance of TVWS in terms of availability and capacity, through these scenarios and more generally, strongly focusing on aggregation of TVWS resources.

A number of key observations result from this paper, some of which we highlight here. First, in the UK, and in Europe in general where local DTT deployment characteristics and landscapes are similar to the UK, TVWS has most benefit potential in below-rooftop receiver and indoor deployments. This is even more so if local white space device (WSD) deployment is extensive. Given this, we define and assess key baseline scenarios that we term as “mobile broadband downlink” and “indoor broadband provisioning” (akin to Wi-Fi or small cells in TVWS). We also argue comparison with other scenarios/topologies through parameter changes. We further demonstrate the strength of TVWS for the indoor case through link performance tests.

A second key observation is that good TVWS availability is achieved through the sophisticated regulatory approach of Ofcom, noting that the same approach to TVWS is harmonized across Europe through the ETSI EN 301 598 standard. However, this is affected by scenario: High power, high transmitter (e.g., >30 m above ground level) scenarios have a particularly reduced and variable availability. High capacities are achieved by aggregating TVWS channels, especially if non-contiguous aggregation is supported. Moreover, profound implications for WSD RF design are derived based on such results, particularly under contiguous aggregation or channel bonding.

A third key observation is that TVWS yields significant future potential, despite headwinds such as the WRC 2015 decision to allocate 694-790 MHz to mobile broadband on a co-primary basis in ITU Region 1, which was nevertheless expected.

Keywords—TV white space, geolocation databases, field trials, spectrum aggregation, spectrum sharing

I. ACT I: “INTRODUCTION”

Progress in TV White Spaces (TVWS) has been propelled forward initially by regulatory steps and deployments of White Space Devices (WSDs) in the US [1], [2]. A large proportion of these deployments are serving scenarios where there is a low population density, e.g., providing broadband coverage over white space to remote communities. There is typically low radio usage and high white space availability in such areas, hence these cases often fit into the Shakespearean analogy of “*some are born with white space*”, requiring relatively less effort to (safely) make use of that white space. Moreover, there are many other WSD deployments internationally that fit into this category, such as the provision of broadband over TVWS to remote communities in Africa, Asia, and elsewhere [2].

In addition to such advances, Europe is proceeding with the finalization of rules and testing of TVWS technology on a large scale [3]–[6]. The European progress is particularly driven by the UK regulator Ofcom's work and instantiation of a large pilot of WSDs and the underlying enabling technology [6]. White space availability in the UK, including TVWS availability in many locations, is extremely challenged by aspects such as locally differing TV broadcast station content sets hence different channel multiplex uses, extensive use of DTT relays, and licensed PMSE (e.g., wireless microphone) usage—taking precedence over WSDs (which are unlicensed, secondary users). Ofcom has therefore created a sophisticated framework for TVWS in the UK, whereby the maximum allowed Equivalent Isotropic Radiated Powers (EIRPs) of WSDs can be varied on a location-basis, given the known locations of victim primary receivers and intricate path loss modelling. This allows WSDs to be used in many channels and locations that would otherwise not be possible with a fixed maximum EIRP limit as is generally assumed elsewhere internationally. Moreover, a range of WSD spectrum masks are supported under the UK/EU framework, allowing the EIRP to be reduced slightly if there is a chance of interference to primary devices in neighboring channels due to the spectrum mask characteristics. This allows far more flexibility in the technical capabilities of WSDs, even facilitating those with poor spectrum masks meaningfully utilizing TVWS.

All of the above characteristics are in line with the UK TVWS case fitting into the category of “*some achieve white*”

space”, against a very challenging situation in terms of spectrum usage and availability, and using a number of sophisticated innovations to realise white space. Further, there are numerous stakeholders in the overall spectrum usage interaction (and particularly in TV bands) that might be affected by TVWS and have the interest in ensuring that the TVWS concept is implemented properly and viably. These include, for example, TV broadcasters such as the BBC, which although wanting to protect the viability and performance of broadcasts, is not inherently anti-TVWS given its large and increasing use of on-demand and other IP-based services. Moreover vociferously, however, they include the PMSE (e.g., wireless microphone) manufacturers, which are generally anti-TVWS. These categories can in some regards be considered as having had “white space thrust upon them”.

Ofcom, as well as striving to “achieve white space” in the challenging spectrum usage situation of the UK for reasons such as to enhance technology and the economy in the UK, is also fundamentally tasked with the avoidance of any form of observable interference to those stakeholders that have had “white space thrust upon them”. Ofcom has therefore been carefully assessing the viability and performance of its framework through a pilot of the technology and framework [6], operating under its prospective rules for WSDs which have been fed into the ETSI EN 301 598 standard [5]. As this is a Harmonized European Standard, these rules for TVWS apply across Europe, meaning that WSDs in other EU countries that intend to operate TVWS must also proceed according to the framework and conformance requirements/tests therein.

Our trial within the Ofcom Pilot is the subject of this paper, providing significant advancement on works published in [7]–[9], and noting that this paper is intended to be the companion paper to [9] in particular. Further, this paper particularly emphasizes work on analysis of what is available in TVWS in the UK (in terms of available number of channels) and what is achievable in TVWS (in terms of performance, capacity) through aggregation of TVWS resource, also toughing on the implications of methodologies for aggregation in TVWS. This paper is structured as follows. The background/reasoning for this paper, including its chosen methodologies, introduction of a select number of publications in past literature, and information on the utilized WSDs, locations and deployment scenarios, are outlined in Section II. Section III presents some results from our trial from the point of view of experimental deployments, and important observations derived from those results. These observations motivate key scenarios that are investigated in Section IV for extraction of availability and capacity analyses, particularly emphasizing aggregation approaches. It is noted that Section IV also briefly investigates changes/implications of other scenarios and topologies. Section V concludes this paper.

II. ACT II: “SETTING THE SCENE”

Our trial has amassed a wide range of WSDs for use over various durations (see, e.g., [7], [8]). However, for the purpose of this paper, the vast majority of our experimental work is done using Carlson RuralConnect WSDs [10], as well as an implementation of the logical aspects of a WSD (including communication with the Ofcom weblisting of GLDBs, and communication with the Fairspectrum GLDB) prepared by

King’s College London and providing a part of the Eurecom ExpressMIMO2 software radios to operate as WSDs [11] as a collaboration with Eurecom. The Carlson RuralConnect devices operate with a Coded OFDM (COFDM) waveform, with modulations 16-QAM, QPSK or BPSK, and with coding schemes of no coding, and $\frac{3}{4}$ -rate or $\frac{1}{2}$ -rate convolutional coding. These modulation/coding schemes are either manually or automatically set by the devices. Moreover, although the devices are proprietary and some specific details of their operation are not known, their lab-tested performance (e.g., throughput, Bit Error Rate—BER) is as would be expected for a quality SISO WSD transmitting on a single 8 MHz channel. These WSDs are therefore good indicators of TVWS performance in general. Further, we constrain our reporting to avoid aspects that are affected by the unknown characteristics of the devices, such as frame/packet error rate for example.

Our trial has also amassed a number of locations for deployment of WSDs as part of our trial [7], [8]. For the purpose of this paper, rooftop sites at King’s College London Denmark Hill Campus, King’s College London Guys (London Bridge) Campus and Queen Mary University of London Mile End Campus have been used to investigate the provisioning of long-distance point-to-point links. Experimentation and long-term provisioning of indoor broadband services in TVWS has been undertaken at King’s College London’s Strand Campus.

This paper assumes a methodical approach to investigation of TVWS in the UK, as well as in the wider EU through the same rules applying on an EU level. We first experiment with long-distance point-to-point links in TVWS, the slightly surprising results of which lead us to undertake measurements of the characteristics of the spectrum in such cases. That work in turn leads to important observations on TVWS characteristics in the UK and other EU countries with similar DTT deployment characteristics, motivating us proceeding with a far deeper investigation of some scenarios that we identify as being of particularly strong usefulness for TVWS. We term these scenarios as:

- Mobile broadband downlink.
 - Akin to, e.g., supplemental downlink in TVWS.
- Indoor broadband provisioning.
 - Akin to small cells in TVWS, Wi-Fi in TVWS, and indoor links to hard-to-reach areas in TVWS.

For these scenarios, we assess white space availability and capacity across London and a wide area of England, through our aforementioned WSD logical implementation to query databases, and rigorous processing of the results. However, we also discuss other scenarios which we deem to be of somewhat reduced interest although still beneficial.

The approach that we take here to measuring white space availability and potential usage cases can be compared with approaches that have been undertaken in the literature, such as [12]. In that paper, and others such as [13], [14], operational aspects and availability of TVWS usage have also been investigated, leading to some very useful and pertinent observations, as well as aspects of analysis of technical solutions (e.g., signalling, channel usage decision making procedures) for TVWS that can address or assist operational challenges. Other papers have provided more of a general analysis of the operational issues for WSDs [15], [16], including aspects such as challenging spectrum masks, sensing

challenges where sensing applies, and geolocation database usage, among others. Further research papers, have projected white space availability based on a number of assumptions about rules that the regulator will put in place [17], [18].

We complement such works and provide a ground-breaking first “real” look as TVWS in the UK, where it is noted that we use analysis from an actual Ofcom-certified GLDB. This can be contrasted with past works, which estimate TVWS availability. Moreover, we note again that such observations can be extrapolated to other EU countries through similar rules, as long as their DTT deployment characteristics are relatively similar to the UK.

III. ACT III: “SOME EXPERIMENTAL RESULTS AND OBSERVATIONS”

Our trial has run in various phases from June 2014, therefore performing a wide range of work. Constraining our reporting towards the main objectives of this paper of assisting and assessing the usage scenarios of TVWS, we progress first in this section with experimental observations that have been made early in our trial, leading to important observations on scenarios for TVWS usage, also providing further experimental work on one scenario that we deem of exceptional interest. For completeness, we provide some minor comment on another aspect we have considered: the potential for WSDs to cause interference to incumbents.

The experimental deployments we assess are: (i) long-distance point-to-point (line-of-sight) links over TVWS, e.g., for broadband provisioning to remote areas, and (ii) indoor deployments such as for broadband provisioning in difficult-to-connect areas of buildings. Such choices might seem very specific, but their extreme natures are deliberately engineered to push the capabilities of TVWS, hence facilitating us making important observations on usage scenarios for TVWS.

A. Long-Distance Point-to-Point (Line-of-Sight) Link Experiments

We first assess long-distance line-of-sight links between King’s College London Denmark Hill Campus and Queen Mary University of London Mile End Campus (7 km distance), and King’s College London Denmark Hill Campus and King’s College London Guys Campus at London Bridge (3.7 km distance). In both cases, UK TV channel 37 was used (center frequency 602 MHz), for which the maximum allowed EIRP returned by the GLDB was 31 dBm. This choice was made because a high level of interference experienced on other channels. More analysis of this pertaining to scenarios for TVWS usage is provided in the next sub-section.

The 7 km link was only just able to be formed. The best rate achieved was around 60 kbps, and the least challenging modulation/coding of the Carlson devices (BPSK, $\frac{1}{2}$ -rate coding) could only achieve a BER of around 1-2%. The best-case SINR was in the range of 8-10 dB, although more typically 10 dB lower. The 3.7 km link enjoyed far better performance, 16-QAM $\frac{1}{2}$ -rate coding achieving a BER of 10^{-6} . Lab testing of the devices indicates that this is equivalent a downlink rate of 6.4 Mbps, and uplink rate of 5.1 Mbps.

For comparison, the ITU terrain loss model over this link gives a link loss in the range of 105 to 110 dB, the various applicable Hata models give losses of in the range of 103 dB

to 141 dB, and free space loss is 105 dB. We have measured the loss over the 7 km line-of-sight tested link, and found that it surprisingly performs very similarly to the Hata Open model—giving a loss in the range of 103 (small/medium city) to 114 dB (large city). Assuming 31 dBm transmission EIRP, a receive antenna gain of 15 dB for the utilized antennas, and a noise power of -105 dBm in a full 8 MHz channel (i.e., the receive radio listening to the entire channel), a relatively poor noise figure of 10 dB still leads to the device achieving an excellent SINR between 27 and 38 dB under the Hata Open model. Lab testing indicates the devices comfortably achieving at or close to their maximum possible performance for such SINRs. The poor performance over this 7 km link therefore surprised us, leading us to deeper inspection of the spectrum situation as reported in the following subsection, thence assessment of scenarios for TVWS usage based on that.

B. Linkage to Scenarios for TVWS Usage

One example of a spectrum survey done by us in response to observations in the previous subsection is given in Fig. 1. This was taken with vertical polarization looking directly South from the Guys London Bridge location, at 50 m height.

To better understand this, an assessment has been undertaken of which TV transmitters are responsible for these power characteristics, including their locations and EIRPs. Our investigation has pointed to 7 DTT transmitters as being mostly if not entirely responsible for the power levels seen in Fig. 1. These are listed as follows:

- Crystal Palace (the transmitter providing intended coverage in the area), on channels 22, 23, 25, 26, 28, 29, 30, 33, 35 (but not on 35 when this particular spectrum survey was done), each with 200 kW EIRP (83 dBm—aside from three channels with lower power), horizontal polarization, central in the peak gain direction of the antenna used in the survey, 8.8 km distance.
- Reigate, on channels 21, 24, 27, 53, 57 and 60, each with 2 kW EIRP (63 dBm), vertical polarization, at 15 degrees to the peak gain direction of the survey antenna, 28.8 km

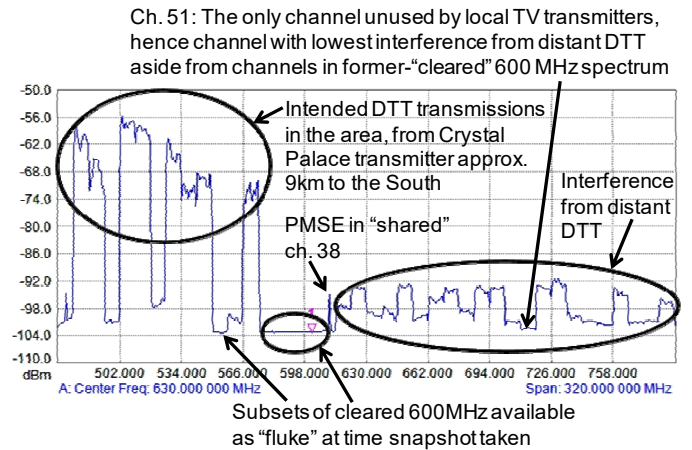


Fig. 1. A spectrum survey performed looking South from the King’s College London Guys Campus hospital tower, clearly showing the intended TV transmissions covering the area, interference from distant DTT transmissions that are not meant to be covering the area, and other characteristics such as a PMSE device transmitting on the shared PMSE channel 38. Covering UK TV band (470-790 MHz), measuring dBm per 30 kHz.

distance.

- Guildford, on channels 40, 43, 46, 48, 49 and 52, each with 2 kW (63 dBm) EIRP, vertical polarization, at 50 degrees to the peak gain direction of the survey antenna, 47.3 km distance.
- Hannington, on channels 32, 39, 41, 42, 44, 45, 47, each with 50 or 25 kW (77 or 74 dBm) EIRP, horizontal polarization, at 75 degrees to the peak gain direction of the survey antenna, 83.4 km distance.
- Heathfield, on channels 41, 42, 44, 47, 48, 52, each with 20 kW (73 dBm) EIRP, with horizontal polarization, at 15 degrees to the peak gain direction of the survey antenna, 65.2 km distance.
- Midhurst, on channels 50, 54, 55, 56, 58, 59, each with 10 or 20 kW (70 or 73 dBm) EIRP, at 40 degrees to the peak gain direction of the survey antenna, 74.1 km distance.
- Bluebell Hill, on 39, 40, 43, 45, 46, 54, each with 20 kW (73 dBm) EIRP, at 60 degrees to the peak gain direction of the survey antenna, 43.5 km distance.

The results in terms of interference (see Fig. 1), given these signal powers and other characteristics of the transmitters, broadly as would be expected via path loss modelling. Moreover, the channel usages of these transmitters, not even taking into account the smaller DTT relays indicated in Fig. 2, cover all 40 TV channels with noticeable power at the observed spectrum survey location—with the exception of channels 31, 34, 36, 37, 38, and 51. All of those channels numbered in the 30's (except, of course, the shared PMSE reserved channel 38) are unused due to the UK 600 MHz spectrum clearance, hence are available as something of a fluke at the particular time of the survey being undertaken—reoccupied again after the 600 MHz auction. This leaves only

channel 51 as being available. Our analysis here matches Fig. 1, with channel 51 clearly having the lowest interference level of all the TV channels according to our survey—again aside from those channels numbered in the 30's.

We have undertaken surveys above rooftops in different locations in the London area and with different antenna configurations, and results have been relatively similar to Fig. 1. Moreover, the situation across the rest of the UK in terms of density of DTT transmitter and relay deployments is very similar to that of the London area, and the landscape is also similar (relatively flat), with the exception of some hilly/mountainous areas such as much of Wales, much of Scotland, and some smaller parts of England, particularly in the North/North-West and South-West of England. We therefore conclude that similar assessments in different locations across the UK will yield a quite similar situation in terms of challenging interference from non-intended coverage DTT transmission stations. However, clearly there will still be many local opportunities with low in-bound interference to receive radios for improved TVWS deployment, such as deployments in valleys that are well shielded from distant DTT transmissions.

The mapping in Fig. 2 of the locations of DTT transmitters covering London and a wider area towards the South and West highlights the complexity of the problem. It is noted here that the underlined transmitters are the main content transmitters, many of which are referred to in the above text, and the non-underlined transmitters are relays, two of which (Reigate and Guildford) are referred to in the above text. All these transmitters (including relays) are configured to use channel multiplexes that are typically lesser-used in their local areas, each typically transmitting on a minimum of 6 (or possibly as

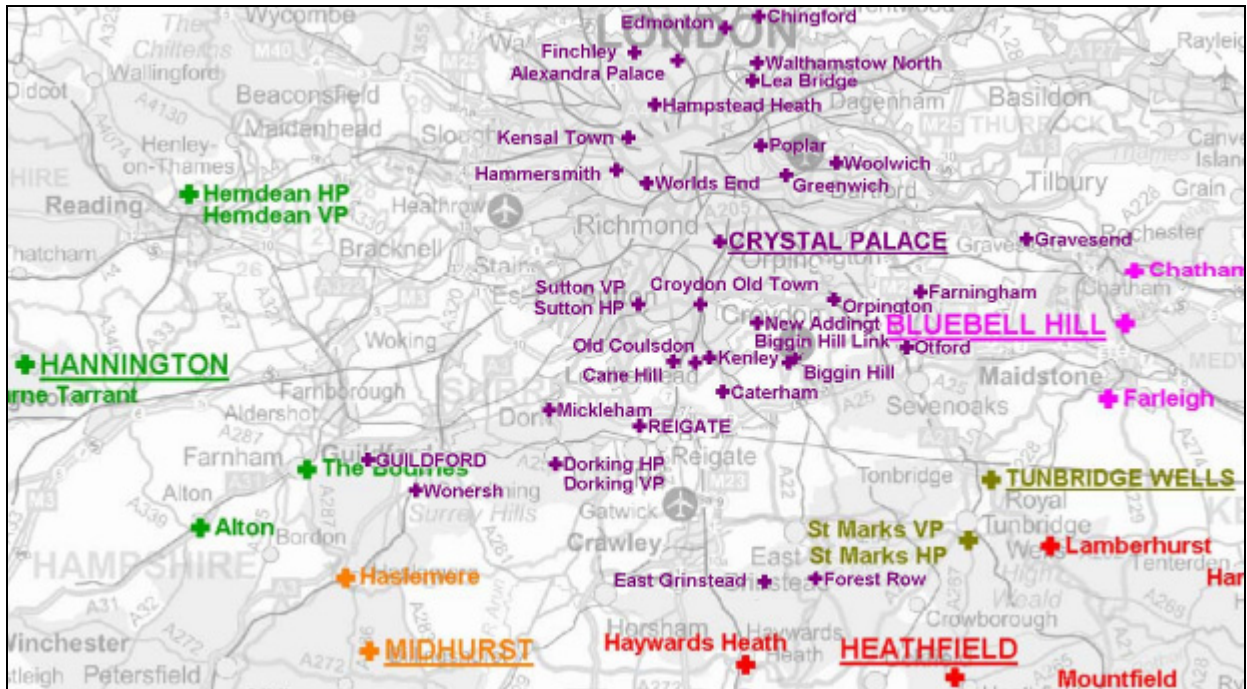


Fig. 2. TV transmitter locations in the London area and towards the South and West of London. Upper case underlined text indicates transmitters of highest power, followed by Upper Case transmitters, followed by others. Image created by graphically merging public domain images provided by Ofcom.

much as 9—e.g., for the Crystal Palace cluster) channel multiplexes. This means that most if not all 40 channel multiplexes (37 of which are potentially available to white space devices) are often visibly transmitted on in the vast majority of locations in the UK.

This observation has implications for the viability of TVWS scenarios where WSD receivers are placed above rooftops, especially if they are aiming to receive very low-power signals. Such receivers will experience noticeable interference in a high proportion of available channels, even for the many locations and channels at which WSDs can operate with maximum EIRP according to the Ofcom/ETSI framework—as borne out by Fig. 1. It is also noted that the situation will get significantly worse due to WSD transmissions interfering with each other as TVWS technology and deployments start to accelerate—effectively polluting the spectrum and raising the “noise floor” for such exposed receive antenna WSDs. It is emphasized here that WSDs have no dominating standard of transmissions politely avoiding each other as there is for IEEE 802.11 devices in 2.4 GHz ISM and 5 GHz U-NII. A range of WSD radio interface standards have been developed, as well as proprietary devices, which potentially interfere significantly with each other. Propagation (of interference) is also vastly better at TV frequencies.

Our 7 km point-to-point link has been affected significantly by this issue, with the interference from distant primary DTT stations (even in the many channels that the WSDs are allowed maximum EIRP on) reducing the received SINR from an excellent value (see the discussion in the previous subsection) by orders of magnitude to negative dB values or lower. Another observation arising from this is that it is highly important to scan the spectrum for the best channel to use, based on the interference situation in channels, before choosing/using a channel. It is noted that some WSDs already support such capability. Indeed, we emphasize that for this long-distance link case, it was far better to use an alternative channel of lower allowed EIRP than one of the numerous channels allowed the absolute maximum 36 dBm, as the lower interference in the lower EIRP channel still led to far better SINR. In our case, channel 37—allowed 31 dBm, 5 dB lower than the absolute maximum—was far better.

Based on such observations, we infer that TVWS in the London area and likely across the vast majority of the UK is most interesting in below rooftop receive radio cases (e.g., downlink provisioning), and shielded scenarios where

propagation characteristics at TV frequencies can be further taken advantage of to greatly improve coverage, such as inside buildings, for example. Finally, it is noted that our observations in this section regarding inbound interference match well with those in the literature, such as [12].

C. Indoor Broadband Provisioning Experiments

Based on the observation that indoor scenarios may be a prime for beneficial TVWS usage, further experimental investigation has been undertaken to assess the benefits and characteristics of TVWS for indoor broadband provisioning. We investigate this scenario particularly because propagation in other cases such as downlink broadband provisioning is already well understood, and expected performance can be relatively easily derived for such cases based on the modelled propagation. Indoor broadband at TV frequencies, however, is not so well understood, hence there is significant added value in performing further work here. Our indoor broadband case is equivalent to the use of small cells or Wi-Fi in TVWS.

This assessment was done at the Strand Campus of King’s College London, which is valuable given its wide range of building types, implementable scenarios, and challenging propagation building characteristics. Fig. 3 depicts the layout of the parts of the Strand and King’s buildings of the Strand Campus considered in this work, as well as the considered links within these buildings. Seven links are investigated in this paper. Link 1 is from the “Flexible Radio” lab of the Centre for Telecommunications Research to the first author’s office, on the same floor and through some 4-5 walls including a closed metal blind covering a high-loss glass wall at the author’s office. The distance of the direct path for Link 1 is approximately 10 m. Link 2 is from the lab to the “Old Committee Room” in the King’s Building, some 20 m away over a partial change in floor level, noting that the King’s Building is of very rugged stone construction. Link 3 is from the lab to the “Council Room”, next door to the “Old Committee Room” and over some 35 m distance. Link 4 is through numerous rooms/walls to the “Refectory”, some 80 m away on the same side of the King’s building as the other end-point of the link, thereby giving potential to use external reflections to improve link performance. Link 5 is across some 90 m in the King’s Building, although mostly guided along a corridor, with a partial change in floor level close to the white space base station location. Link 6 is to inside the “Staff Common Room” the new end-point being close to the prior end-point of Link 5 outside. Link 7 is to a classroom on the second floor of the Strand Building, transmitting diagonally up through at least 3 walls/floors, and across by some 10 m.

Results of the various performance stability tests under various modulation and coding schemes, as well as link throughput and SINR range assessments, are given in Table I. We discuss the performance of these links in more detail here. This is firstly to demonstrate the excellent performance that TVWS can achieve in such indoor deployments, even in challenging cases transmitting through thick stone walls, and secondly to highlight some of the key characteristics that we have observed to influence that performance.

Links 1 and 2 achieve close to the maximum achievable performance for the Carlson WSDs—providing that the building is not too busy at the time of testing. The high variation in throughput performance for Link 2 is caused by

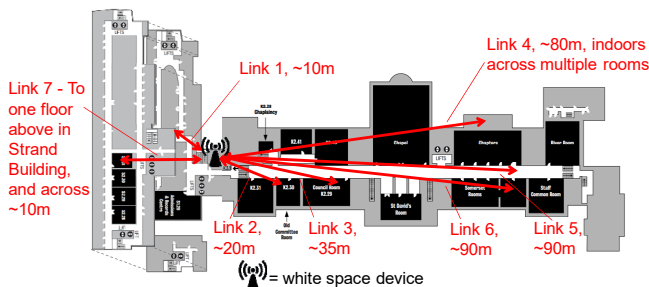


Fig. 3. Indoor plans of the Strand and King’s buildings (combined) of the King’s College London Strand Campus. The Strand Building is to the left of the WSD, and the King’s Building is to the right. Both the 1st and 2nd floors of the Strand Building are depicted, whereas only the 2nd floor of the King’s Building is depicted.

additional people (students/staff) being in the building and on the link path for some of the duration that the throughput was being measured, leading to the link falling back to additional coding. Moreover, for these links under throughput testing, the WSDs defaulted to 16-QAM with no coding if configured to automatically select modulation and coding rate, except for the aforementioned exceptional cases for Link 2. This phenomenon of people in the building affecting the link quality is also reflected at the time of the modulation and coding assessments for Link 1, reducing the expected performance for the 16-QAM modes. Nevertheless, for both Links 1 and 2, no other modulation and coding modes were tested given the already good performance in the tested modes of operation and other modes being less challenging. Link 3 achieves somewhat worse performance than Link 2, as would be expected. This link is also challenged by transmission through a wall at more of an acute angle compared with link 2, hence having more obstacle to travel through.

Link 4 is highly variable depending on the antenna optimization, from achieving poor performance (although still usable) to achieving performance rivaling the best that the Carlson devices are capable of. This is because it is possible, through optimizing the antenna orientations, to achieve good reflections of the signal—using buildings outside—between the antenna end-points situated some distance away inside on

the same side of the building.

Link 5's performance was generally poor but extremely variable, given that it was mostly along a long corridor and the number of people in that corridor varied significantly. This is reflected in the later SINR distribution assessments in Fig. 4. Emphasizing the importance of antenna placing, moving the antenna endpoint only 1.5m away to a neighboring room to the corridor (Link 6) caused the link to become unusable. Further, although the distance of Link 6 is quite similar to Link 4, the presence of the end-points on different sides of the building for Link 6, hence the complete lack of external reflections assisting the link, leads to the link being unusable.

Finally, Link 7 achieved almost optimum performance for the Carlson devices. Moreover, this link was incredibly stable, given that its trajectory diagonally between floors minimized the potential for humans to interfere with its propagation.

On a separate occasion, we assessed the SINR distributions (Complementary Cumulative Distribution Functions—CCDFs) achievable for a subset of the links (see Fig. 4). Based on this, Link 1 exhibited a high variability in SINR, although 24-25 dB at a minimum; this was due to variations in people in the building and relatively near one of the antennas. More typically, the SINR for Link 1 was in the range of 28-32 dB. Link 2 showed a low variability with SINR constrained in the range 27-31 dB; however, it is noted that at the time of this

TABLE I: EXPERIMENTALLY-MEASURED PERFORMANCES FOR INDOOR BROADBAND PROVISIONING (UNTESTED BIT ERROR AND PACKET ERROR RATE MODULATION AND CODING CASES ARE DUE TO PERFORMANCE ALREADY BEING EXCEPTIONAL IN MORE CHALLENGING CASES, HENCE TESTING BEING UNNECESSARY)

Link	Average Bit Error Rate (BER)									Throughput Range (Mbps)		SINR Range (dB)
	16-QAM no coding	16-QAM $\frac{3}{4}$ coding	16-QAM $\frac{1}{2}$ coding	QPSK no coding	QPSK $\frac{3}{4}$ coding	QPSK $\frac{1}{2}$ coding	BPSK no coding	BPSK $\frac{3}{4}$ coding	BPSK $\frac{1}{2}$ coding	Downlink	Uplink	
1	BER 2.7×10^{-3} ^a	BER 3.1×10^{-3} ^a	BER 1.2×10^{-3} ^a	Not tested ^b	Not tested ^b	Not tested	Not tested	Not tested	Not tested	6.5-8.3 (up to 11.5 with new firmware)	2.6-3.2	24 to 32
2	BER 3.5×10^{-9} ^a	Not tested ^b	Not tested ^b	Not tested	Not tested	Not tested	Not tested	Not tested	Not tested	5.7-9.9	1.0-2.2	27 to 32
3	BER 1.1×10^{-3}	BER 3.5×10^{-6}	Not tested ^b	BER 2.2×10^{-4}	No bit errors observed	Not tested	Not tested	Not tested	Not tested	3.3-9.1	1.1-2.5	25 to 31
4	BER 4×10^{-3}	BER 2.4×10^{-5}	BER 4.0×10^{-6}	BER 1.5×10^{-6}	No bit errors observed	Not tested	Not tested	Not tested	Not tested	Approx. 1-2	Approx. 0.1-0.4	16 to 21
4 (optimized antenna orientations)	BER 8.8×10^{-6} ^a	No bit errors observed	Not tested	Not tested	Not tested	Not tested	Not tested	Not tested	Not tested	Approx. 9-10	Approx. 1-2	27 to 31
5	BER 2.3×10^{-2}	BER 1.5×10^{-2}	BER 1.2×10^{-2}	BER 3.7×10^{-4}	BER 1.0×10^{-3}	BER 1.9×10^{-5}	BER 1.0×10^{-3} ^a	BER 2.5×10^{-5}	Not tested	Not tested ^c	Not tested ^c	7 to 24
6	Unusable (packet errors 100%)	Unusable (packet errors 100%)	Unusable (packet errors 100%)	Unusable (packet errors 100%)	Unusable (packet errors 100%)	Unusable (packet errors 100%)	BER 1.5×10^{-3}	BER 2.3×10^{-2}	BER 2.7×10^{-3}	Not tested ^c	Not tested ^c	-7 to 13
7	Not tested ^b	Not tested ^b	Not tested ^b	Not tested	Not tested	Not tested	Not tested	Not tested	Not tested	10.0-12.5 (new firmware)	1.4-2.6 (new firmware)	Not tested ^b

^a Many of these results are being reassessed to ensure most appropriate scenario, e.g., number of staff/students interfering with the link path, and to ensure there were no unexpected factors causing discrepancies – the experiments will be completed by the time of final camera-ready paper submission, if accepted. It is not expected that this reassessment will lead to any noticeable change in the conclusions or observations linked to these results.

^b The assessment of these additional results by the time the camera-ready paper is due (if the paper is accepted) is being considered.

^c These results would generally yield very low performance (especially link 6, for which it is expected to be extremely difficult to even form a data connection). However, if the reviewers think it useful, they could be evaluated at a later stage for the camera-ready version of this paper, if accepted.

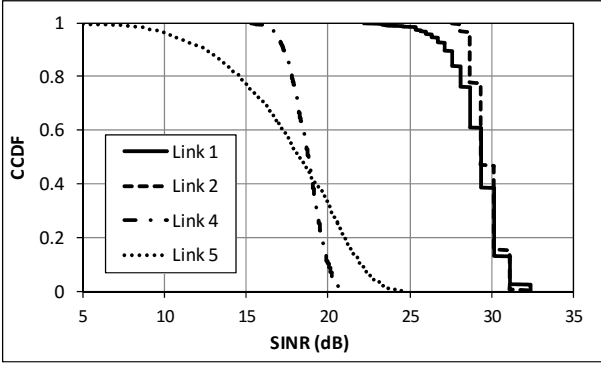


Fig. 4. CCDFs of received SINRs for some of the assessed links.

additional assessment there were very few people in the building. Link 5, largely guided by the long corridor in the King’s Building, showed an immense variability depending on the number of people in the corridor that the link passed through, noting that this assessment of Link 5 at a busy time. SINR here was at least 7 dB but occasionally up to 24 dB. Link 4, using a typical non-optimized antenna configuration, showed a more stable but quite low SINR of at least 16 dB.

D. Coexistence with Primary Services

“Some have white space thrust upon them”. Amidst this claim, we have attempted to assess one aspect of potential interference from WSDs, namely, neighboring channel interference in worst case scenarios. We concentrate on this in the knowledge that co-channel interference is being sufficiently dealt with through established path loss modelling and other efforts within Ofcom, incorporated within the Ofcom framework and the decisions that the GLDBs make on allowed transmission power in each channel.

Various experiments concerning coexistence testing with primary DTT and PMSE services have been done by our trial. One scenario is to assess interference to primary services caused by power leakage into adjacent channels, with a WSD transmitting at maximum allowed power in the adjacent channel and performance of the primary service (audio/video quality) being digitally recorded or otherwise statistically assessed. We have used the most geometrically challenging configurations possible in attempting to cause interference to the primary services, for example, mounting the WSD antenna and TV receive antenna on the same pole 10cm apart for DTT interference assessment. Some initial results and more detail are in [8]; the key point is that it has been impossible to observably interfere with DTT or PMSE services.

IV. ACT IV: “WHITE SPACE AVAILABILITY, CAPACITY AND AGGREGATION STUDIES”

“Some achieve white space”. On this topic, key questions are: How much white space is there under the UK/EU framework, and what can be achieved using that white space? These are all the more important to answer for the UK/EU case, which operates under significantly different rules from the US and other similar deployments that are for the most part all broadly based on variations to US rules.

To shed some light on this, we have investigated the available white space in the London, UK area, and also the

TABLE II: SCENARIO CONFIGURATIONS

	Trans. Height (m)	Rec. Height (m)	Trans. Distance (m)	Required EIRP (dBm)	Path Loss	Shan. Efficiency
Mobile Broadband Downlink	30	1.5	2,000	>30	Hata large-city urban	0.5
Indoor Broadband Provisioning	1	1	80	>20	Yamada, 8 walls, same floor, King’s College Strand parameters [19]	0.5

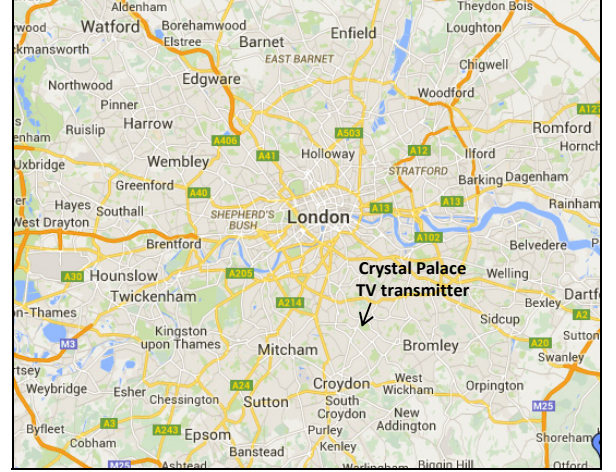


Fig. 5. The investigated London M25 area for availability, capacity and aggregation studies.

optimum capacity that can be achieved by aggregating all of that white space. Our studies have sampled white space availability according to the UK framework in a rectangular lattice with the top-left corner (latitude, longitude) 51.678064, -0.506744, bottom-right corner 51.312133, 0.229340, and sampling frequency of 0.01° both in latitude and longitude. This equates to the area approximately as bounded by the London M25 orbital motorway/highway, and 2,775 sampled locations in that area. Fig. 5 maps the considered area. For comparison, this work has been extended and reported later in Section IV.D to consider a much larger area of England.

We have adapted one of our implementations of the WSD-side logical requirements, in order to methodically query Fairspectrum and obtain information on available white space, and do capacity analyses with a particular emphasis on aggregation scenarios. This work is based on the Ofcom Framework as was the case in January 2015.

We study two scenarios, which we term the “mobile broadband downlink” and “indoor broadband provisioning”, for reasons such as reported in Section III.B. The mobile broadband downlink scenario is further inspired by the efforts made towards the realization of LTE supplemental downlink scenarios albeit initially in the form of LAA unlicensed access in 5GHz U-NII spectrum. Given this, TVWS can be a facilitator for enhancing capacity, conveniently located extremely close to the LTE 700 and LTE 800 spectrum thereby facilitating design of LTE devices should they wish to use TVWS for a supplemental downlink. The indoor broadband provisioning scenario mirrors a number of

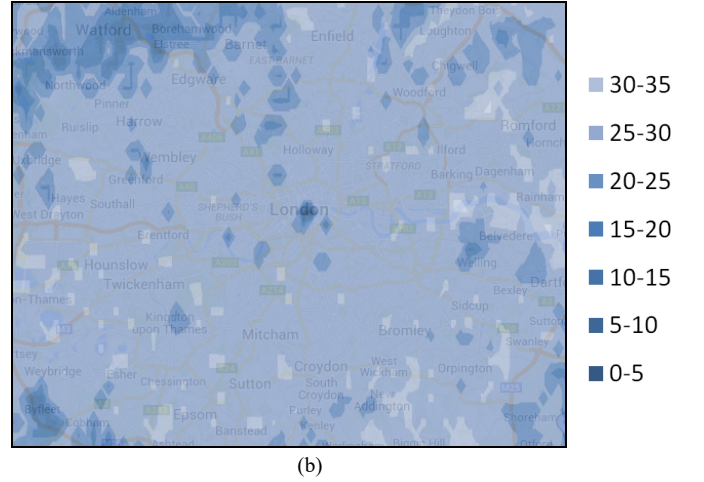
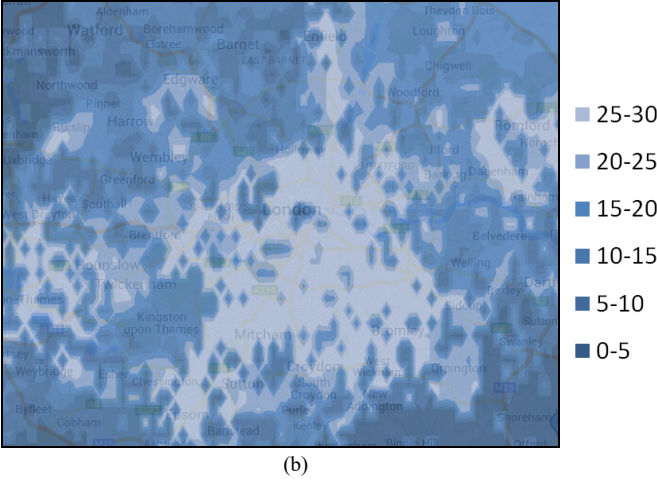
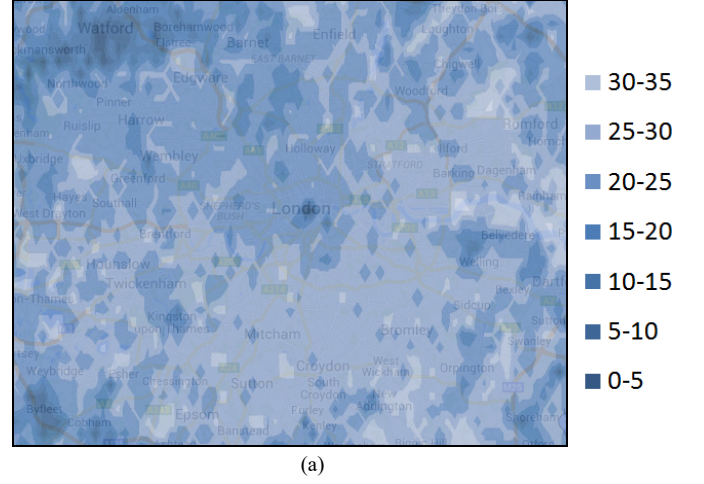
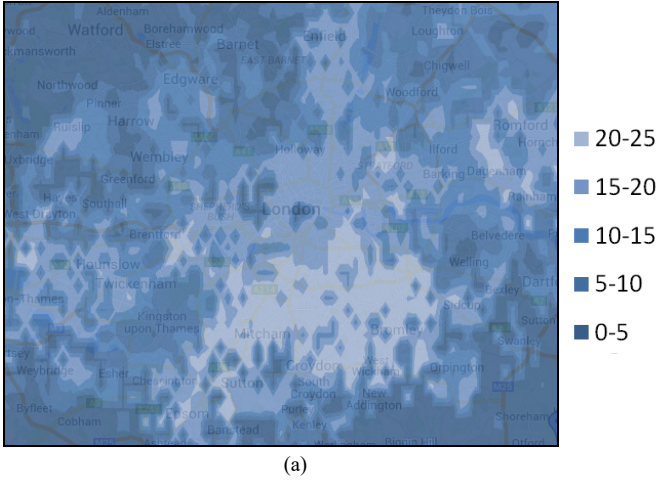


Fig. 6. Number of “usable” channels available for the mobile broadband downlink scenario: (a) Class 5 device, (b) Class 1 device.

Fig. 7. Number of “usable” channels available for the indoor broadband provisioning scenario: (a) Class 5 device, (b) Class 1 device.

deployment cases such as stated in Section II. Further, in addition to the consideration of these particularly preferable scenarios for TVWS, in Section IV.D(2) we provide discussion on generalization to other scenarios that are likely beneficial, through arguing the effects of parameter changes.

The characteristics of our two key these scenarios are given in Table II. Transmitter height here is used by the GLDB (in addition, of course, to location and others such as spectrum mask class) in assessing allowed powers on a per-channel basis, whereas the receiver height is used merely for propagation loss calculations, and the Shannon efficiency of the radio interface is for capacity calculations. Moreover, propagation characteristics are deliberately challenging for the given scenarios, where the mobile broadband downlink scenario uses the highest-loss variant Hata propagation model over a propagation distance of 2 km. The indoor broadband scenario uses a propagation model for indoor TVWS transmissions developed at King’s College London, and parameterized at the Strand building of King’s College [19]. For this scenario and parameterization, this model has been shown to perform far better than available alternatives [19]. Given these challenging characteristics, capacity analyses for both scenarios give worst-case results.

TABLE III: STATISTICS ON NUMBER OF “USABLE” CHANNELS AVAILABLE FOR THE MOBILE BROADBAND DOWNLINK SCENARIO, FOR ALL DEVICE SPECTRUM MASK PERFORMANCE CLASSES

Number of channels					
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	15.6	15.4	15.2	12.6	10.2
STD	8.4	8.4	8.5	8.1	7.1
CoV	0.54	0.55	0.56	0.64	0.70

TABLE IV: STATISTICS ON NUMBER OF “USABLE” CHANNELS AVAILABLE FOR THE INDOOR BROADBAND PROVISIONING SCENARIO, FOR ALL DEVICE SPECTRUM MASK PERFORMANCE CLASSES

Number of channels					
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	25.7	25.6	25.5	24.9	23.4
STD	3.4	3.4	3.6	4.2	5.2
CoV	0.13	0.13	0.14	0.17	0.22

A. Number of Channels available

Fig. 6(a) maps the number of channels that are available for the mobile broadband downlink scenario (assuming a minimum allowed EIRP of 30 dBm), over the London M25 area corresponding to that in Fig. 5, for a Class 5 device. Fig. 6(b) presents the equivalent for a Class 1 device, and Table III gives statistics over the area for all classes of devices. Fig. 7 and Table IV present the same results for the indoor broadband provisioning scenario, assuming a minimum allowed EIRP of 20 dBm in assessing channel availability.

One first clear observation from these results is that Classes 1-3 are very similar in terms of availability, with availability only starting to significantly reduce for Classes 4 and 5. Moreover, it is noted that there is a very good correlation of availability with the location of the main London TV transmitter at Crystal Palace (marked in Fig. 5). This is because there is one TV transmitter providing sole coverage in the area hence not other TV transmitters/relays blocking out different sets of channels to achieve their multiplexes thereby reducing white space availability, noting that in the UK the different TV transmitters and relays use different frequencies in order to avoid interfering with the reception of each other, and also to provide different content to different regions. Comparing with the north-west and south-west of the assessed London area, availability is reduced significantly because of the overlap of TV transmitter coverage for those areas, and the reduced propagation loss. An extreme case is presented for the Guildford location discussed later in Fig. 10, whereby there is severe overlap of various TV transmitters, and availability is reduced significantly.

Another observation is that there are a large number of relatively small “spots” of reduced availability. These are caused by PMSE (e.g., wireless microphone) deployments, noting that PMSE is also licensed and deployment locations known in the UK, hence is protected to the same level as TV broadcast services. The most severe such location is part of the “West End” area of London, incidentally coinciding with the South Aldwych/Strand area and the King’s College London Strand Campus, covered extensively in later discussion. This is the area a quarter of the way down and on the right side of the letter “d” of “London” in Figs. 4-8. This reduced availability is due to PMSE usage of numerous nearby musical theatres, concert halls, TV production, among others facilities.

Concerning statistics on availability reflected in Tables III and IV, it is noted that for the mobile broadband downlink scenario an average of approximately 10 to 15 channels is available depending on class; the coefficient of variation (CoV) of this number increases somewhat from 0.54 to 0.70 as spectrum mask performance class is reduced. For the indoor broadband provisioning scenario, an average of approximately 23 to 26 channels are available, with a coefficient of variation increasing from 0.13 to 0.22 as spectrum mask performance class is reduced. Hence, the indoor broadband provisioning scenario achieves both greater availability on average, and better certainty in the availability of spectrum. There is somewhat of a reduction in such availability as the transmitter height is increased, however, that is not significant. Moreover, it is noted that the reduced EIRP requirement for the indoor broadband provisioning scenario is the key cause of greater certainty, leading to a reduced number of locations for which

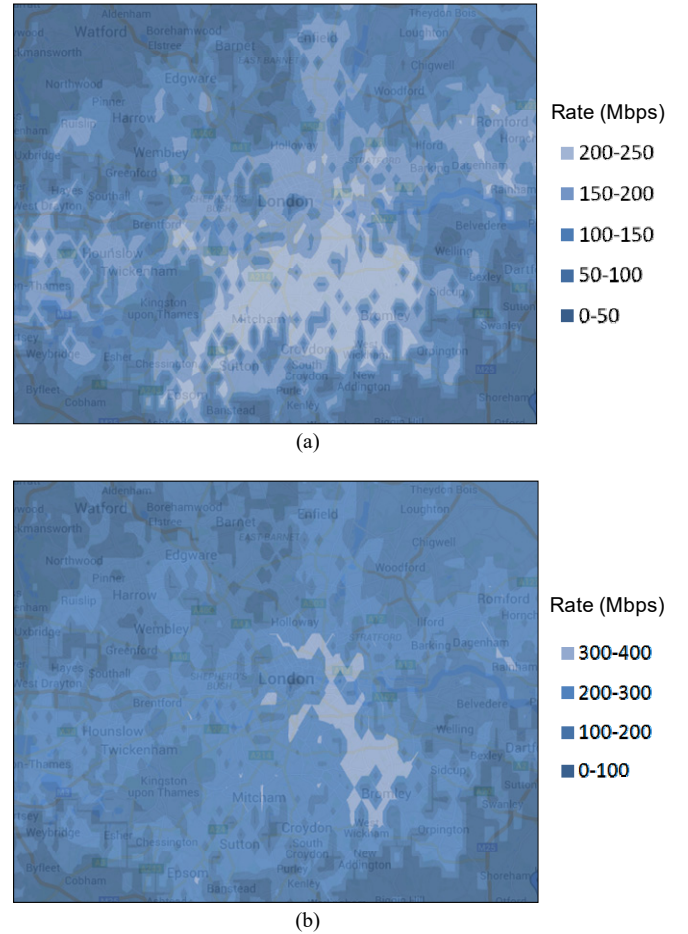


Fig. 8. Capacity achievable by optimally aggregating all available channels at maximum allowed EIRP on a per-channel basis for the mobile broadband downlink scenario: (a) Class 5 device, (b) Class 1 device.

PMSE and TV primary services impact on the allowed EIRP enough to violate the 20 dBm threshold.

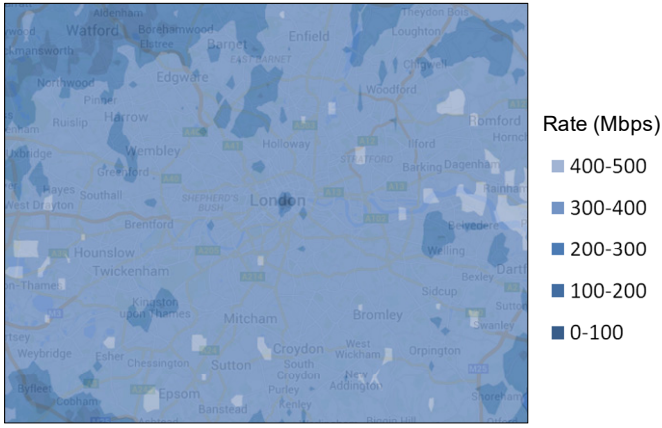
A further observation is that a worsening of spectrum mask class has a far more severe effect for the mobile broadband downlink scenario, as compared with the indoor broadband provisioning scenario. This conveniently matches with the observation that white space base station deployments for the mobile broadband downlink scenario will be relatively sparse, and be able to absorb a greater expense in achieving a good spectrum mask class. Radio deployments for the indoor broadband provisioning scenario will be very dense, and typically done only by the consumer/end-user. Expense here must be minimized, which seems achievable given that deployment of a Class 5 device, for example, generally has little effect on performance as compared with Class 1.

B. Achievable Capacity

Next assessed are the achievable capacities for the mobile broadband downlink and indoor broadband provisioning scenarios. In all cases, capacity calculations are done assuming “optimal” aggregation of *all* channels at maximum allowed EIRP on a per-channel basis. The previously indicated



(a)



(b)

Fig. 9. Capacity achievable by optimally aggregating all available channels at maximum allowed EIRP on a per-channel basis for the indoor broadband provisioning scenario: (a) Class 5 device, (b) Class 1 device.

TABLE V: STATISTICS ON ACHIEVED BATE BY OPTIMALLY AGGREGATING ALL AVAILABLE CHANNELS AT MAXIMUM ALLOWED EIRP ON A PER-CHANNEL BASIS FOR THE MOBILE BROADBAND DOWNLINK SCENARIO, FOR ALL DEVICE SPECTRUM MASK PERFORMANCE CLASSES

Achieved Rate (Mbps)					
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	167.0	165.1	155.4	130.9	104.7
STD	84.2	84.4	82.5	77.4	66.8
CoV	0.50	0.51	0.53	0.59	0.64

TABLE VI: STATISTICS ON ACHIEVED BATE BY OPTIMALLY AGGREGATING ALL AVAILABLE CHANNELS AT MAXIMUM ALLOWED EIRP ON A PER-CHANNEL BASIS FOR THE INDOOR BROADBAND PROVISIONING SCENARIO, FOR ALL DEVICE SPECTRUM MASK PERFORMANCE CLASSES

Achieved Rate (Mbps)					
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	333.5	330.9	327.5	312.5	285.6
STD	54.9	55.6	58.8	65.4	67.9
CoV	0.16	0.17	0.18	0.21	0.24

challenging propagation characteristics are assumed (see Table II) as a “worst case” scenario.

Achieved aggregate capacity mapped to the locations in the London M25 area for the mobile broadband downlink scenario is given in Fig. 8, and for the indoor broadband provisioning scenario in Fig. 9. Corresponding tables of statistics are in Tables V and VI. It is noted that many of the same observations as are made in the analysis of available number of channels apply. However, there are some differences. For example, more of a negative effect is observed if the spectrum mask class is reduced from Class 2 to Class 3 for the mobile broadband downlink scenario. This is because there are reduced EIRPs for Class 3 devices, hence reducing the capacity that is achievable by aggregating channels at maximum allowed EIRP, however, these reduced EIRPs rarely fall below the threshold of 30 dBm to rule the channels as “not available” under this scenario as we define it.

Extending observations from the analysis of the number of channels available, Class 1 and Class 2 performances remain almost identical, both in terms of average number of channels and capacity and in terms of variability of those, although in the case of the analysis of the capacity achieved Class 3 performances are reduced somewhat. This leads to the conclusion that, given a relatively “noisy” design of WSD, there would be little benefit gained by striving for the more challenging -79 and -84 dB requirements in further-out channels than the adjacent channel, if the device already achieved -74 dB in the adjacent hence other channels. Moreover, it is noted that the -74 dB requirement in the Ofcom UK/EU case is equivalent to -55 dB in the FCC US case, due to the Adjacent Frequency Leakage Ratio (AFLR) being measured for 100 kHz “bins” in adjacent channels as compared with the 8 MHz value in the intended channel under the UK model. Hence, AFLR is already automatically 19 dB (80x) lower in a like-for-like power spectral density comparison. It should be noted, however, that the UK/EU case additionally requires that there is no EIRP density limit violation in any of the “bins”.

1) Aggregation Options

Next assessed is the performance that is achieved through implementing various aggregation configurations in TV white space. Fig. 10 presents the achieved capacity for the mobile broadband downlink scenario against the number of channels that are aggregated for a small (example) subset of the deployment locations we use in our trial. Fig. 10 assumes either contiguous or non-contiguous aggregation (i.e., that the radio can take advantage of all channels optimally with maximum allowed EIRP on a per-channel basis, no matter how they are distributed across the frequency band). This could be seen as feasible, for example, under an advanced radio interface such as filter-bank multi-carrier [20], able to “notch out” certain channels and still use those available ones at precisely the power limit. A very simple channel selection rule ascertains the next available channel to use:

1. Choose the channel with maximum allowed EIRP according to the UK framework.
 - a. If EIRP is equal among the next available channels (note, this is common under the UK framework, as EIRPs are given as integer dBm values), choose the channel of

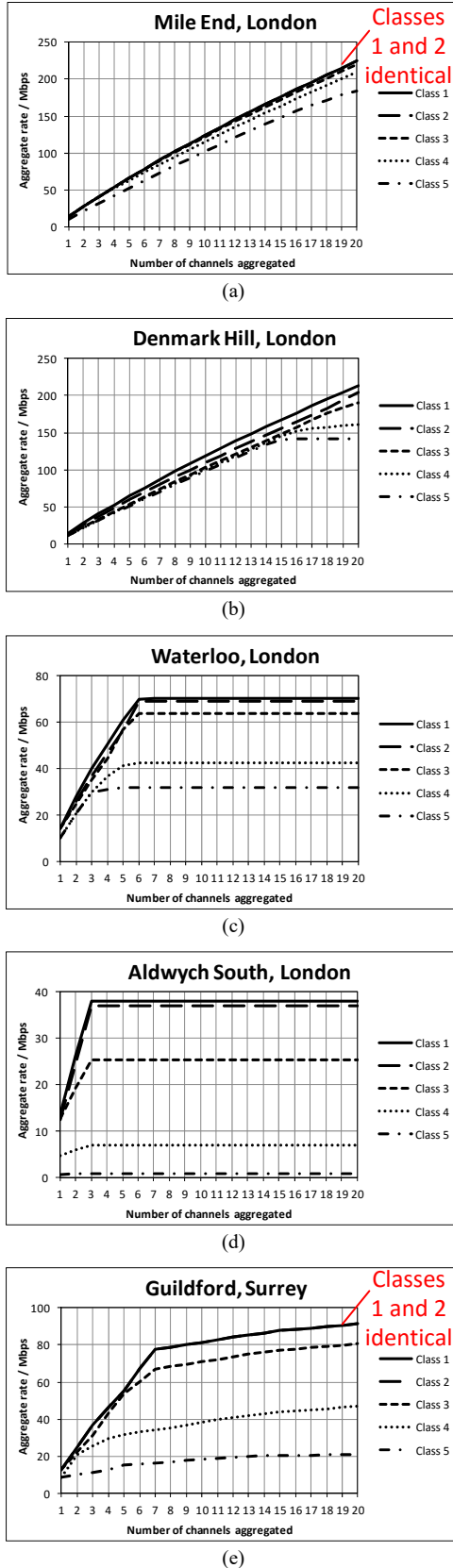


Fig. 10. Capacity achievable by optimally aggregating different numbers of channels at maximum allowed EIRP on a per-channel basis for the mobile broadband downlink scenario, at some specific locations.

equal highest EIRP and lowest frequency.

Results for the cases in Fig. 10 are presented in the order of the most favorable to the least favorable for aggregation (or, indeed, often for TVWS usage in general). Considering the results for Mile End in Fig. 10(a), this is the best location for white spaces usage among those assessed. Performance increases almost linearly with the number of channels that are aggregated, with a slight drop-off in performance for worse performance spectrum mask classes due to increased adjacent channel leakages, either (i) ruling out some lower frequency channels at equal power for aggregation, meaning that higher-frequency (worse propagation/performance) channels have to be used at equal power, or (ii) in some rare cases causing a reduction in allowed power in order to maintain adjacent channel leakage requirements.

For the Denmark Hill case, the beginning of cases where the limit on the number of channels that can be used for aggregation is observed, for poor spectrum mask classes due to the adjacent channel leakage requirements. Class 4 performance here represents a worsening of the phenomena seen for Mile End case under poorer performance classes, whereas the “flat-lining” of the Class 5 case indicates that the limit has been hit. The Waterloo and South Aldwych cases show the situation where a large number of channels are ruled out due to extensive PMSE usage in the area, the South Aldwych case being a particularly severely affected example. Moreover, PMSE usage seems to be cause of the relatively-abrupt flat-lining for the Denmark Hill case observed.

The Guildford case here represents what is seen when the limitations are largely due to DTT, Guildford white space being severely affected by overlapping DTT transmitter coverages transmitting multiplexes at different frequencies. This DTT limitation on white space usage leads to a reduction in EIRPs on many channels, but not the flat-lining that PMSE usage leads to as has been observed for the South Aldwych, Waterloo, and somewhat the Denmark Hill locations.

A further observation from these results is that, again, Classes 1 and 2 lead to very similar, if not identical, performance. Particularly in cases where potential interference victims are more than a certain distance away (e.g., in the Guildford case) the performance is identical. This is because at more than a certain (very short) distance, the -79 and -84 dB down limitations for further-out channels than the adjacent channels no longer have an effect, as received power at victim receivers has already dropped below the level of harmful interference without additional limitations.

Fig. 11 represents the case where the WSD can only aggregate contiguous channels, e.g., should it have only one radio that can transmit contiguously, which is of variable bandwidth. Under this case, the following algorithm has been used for choosing channels and powers:

1. For all possible sets of n contiguous channels.
 - a. Ascertain the EIRP of the lowest allowed among the contiguous channels.
 - i. Transmit on all of the contiguous channels with this equal lowest power, even if some of the contiguous channels support higher allowed power. This is necessary in order to not violate regulatory

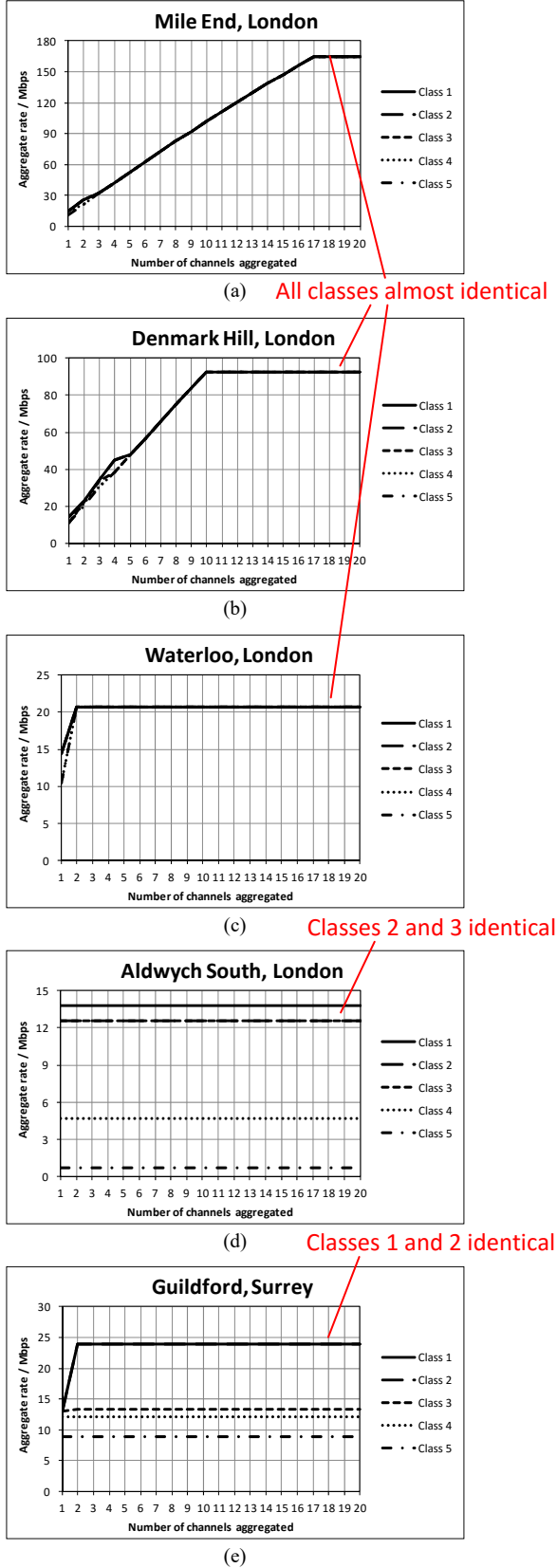


Fig. 11. Capacity achievable by aggregating different numbers of contiguous-only channels for the mobile broadband downlink scenario, at some specific locations.

limits on a per-channel basis, assuming that the radio produces a relatively “flat” waveform over the allowed channels.

2. Perform the same operation as in Step 1 for $n-1$, $n-2$, etc., to $n=1$ contiguous channels.
3. Take the result of the highest rate among all possible sets of contiguous channels assessed in Steps 1 and Step 2 above as the achieved value for n contiguous channels.

One key initial observation is that except for rare examples (e.g., Guildford), class doesn’t have a major effect on capacity achievable. This result, which is backed up by later results in Section IV.D, has profound implications for the design of WSDs: there is often little to be gained by striving for higher performance classes than Class 5, given the significant RF complexity that that implies. A manufacturer designing a device with the ability to aggregate 3 or more contiguous channels (bandwidth) can neglect the adjacent channel leakage increase that might often occur if the bandwidth is being increased, reducing the spectrum mask class. However, such an observation depends on the required guarantee of service for the white spaces system, as in some cases, particularly where there are a small number of dispersed channels available (e.g., the Aldwych South case) or cases where multiple TV transmitters are overlapping, the out-of-channel emissions can infringe on the primary services more under the algorithm above, hence class playing a more important role. Generally, an overriding observation is that, as the number of contiguous channels available to aggregate increases, distance to primary victim receivers quickly becomes the limiting factor rather than the out-of-channel emissions, rendering class to be of lesser or no importance.

C. Did WRC 2015 Kill TV White Space?

A penultimate availability/capacity study done here is to assess the effects that WRC 2015 (which took place in November 2015) will eventually have in a worst case scenario. At WRC 2015, the allocation of 694-790 MHz to mobile broadband on a co-primary basis for ITU Region 1 (which includes the UK and wider EU) was decided, although that decision had been expected ever since WRC 2012. Should all of that spectrum be taken by mobile broadband and not be available to WSDs, this would rule out UK channels 49-60. In this section, we therefore perform a further study on available channels and achievable capacity if channels 49 and above are ruled out. Exactly the same prior assumptions, parameterizations, and investigated London M25 area apply. Moreover, it is noted that most of the area investigated is dominated by the Crystal Palace transmitter (and not relays thereof), whereby all of the channels that Crystal Palace is transmitting on are below channel 49. Hence, the effect of repackaging of TV transmitters in order to handle the ruling out of channels above channel 48 is relatively small, noting also that it is impossible to accurately predict exactly how the TV transmitters (including relays) will be repackaged, therefore ruling out an analysis that includes repackaging.

Results under this assumption are presented in Tables VII and VIII for the mobile broadband downlink scenario, and Tables IX and X for the indoor broadband provisioning scenario. One key observation is that, for the mobile

TABLE VII: STATISTICS ON WORST CASE WHITE SPACE AVAILABILITY AFTER WRC 2015 FOR THE MOBILE BROADBAND DOWNLINK SCENARIO.

Number of channels					
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	8.5	8.4	8.1	5.6	3.6
STD	5.0	5.0	5.1	4.6	3.5
CoV	0.58	0.60	0.62	0.82	0.96

TABLE VIII: STATISTICS ON WORST CASE ACHIEVED AGGREGATE CAPACITY AFTER WRC 2015 FOR THE MOBILE BROADBAND DOWNLINK SCENARIO.

Achieved Rate (Mbps)					
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	102.2	100.4	90.8	67.4	43.7
STD	53.0	53.4	51.5	46.3	34.0
CoV	0.52	0.53	0.57	0.69	0.78

TABLE IX: STATISTICS ON WORST CASE WHITE SPACE AVAILABILITY AFTER WRC 2015 FOR THE INDOOR BROADBAND PROVISIONING SCENARIO.

Number of channels					
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	14.1	14.1	14.0	13.3	12.0
STD	2.6	2.7	2.8	3.4	4.2
CoV	0.19	0.19	0.20	0.26	0.35

TABLE X: STATISTICS ON WORST CASE ACHIEVED AGGREGATE CAPACITY AFTER WRC 2015 FOR THE INDOOR BROADBAND PROVISIONING SCENARIO.

Achieved Rate (Mbps)					
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	165.4	163.0	160.0	146.2	121.5
STD	36.8	37.6	40.3	45.2	43.4
CoV	0.22	0.23	0.25	0.31	0.36

broadband downlink scenario, the effect—particularly for lower classes of RF performance—could be severe. In particular, even in some London suburb areas (not considering other further-out/challenging cases such as the previously-discussed Guildford case) large parts of the area, particularly in the North-West and South-West suburbs, have zero channel availability with allowed power of over 30 dBm. Further, there is a significant increase in uncertainty in availability of both channels and achievable capacity for both scenarios.

Under the indoor broadband provisioning scenario, the effect is less severe. However, there is a reduction in both the number of available channels and achievable capacity as would be expected. The effect on the variability of availability/capacity is also less severe although is noticeable.

Regarding these results, the worst-case nature of them cannot be overemphasized. For example, there are uncertainties as to whether WSD usage would remain allowed in this co-primary band, and if it were allowed, the extent to which access would be taken up by mobile operators and the resulting availability of white space in this band.

D. The Bigger Picture

Finally, in this section, we attempt to broaden this analysis in three areas: (i) expansion of the area of assessment, (ii) consideration of alternative scenarios, and (iii) comparison with the literature.

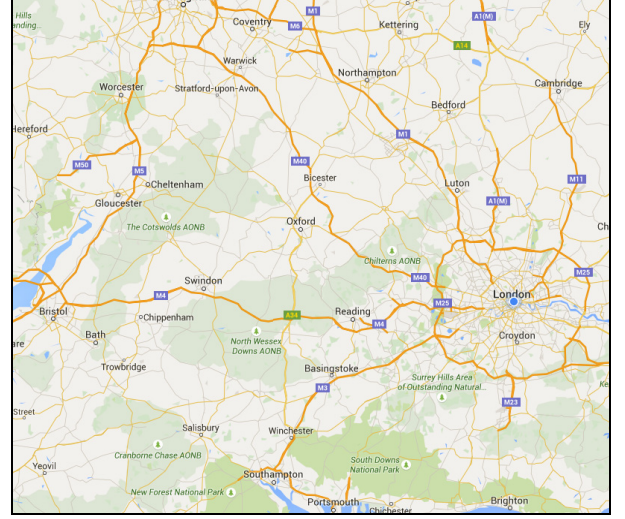


Fig. 12. The investigated wider area of England for availability and capacity comparison studies.

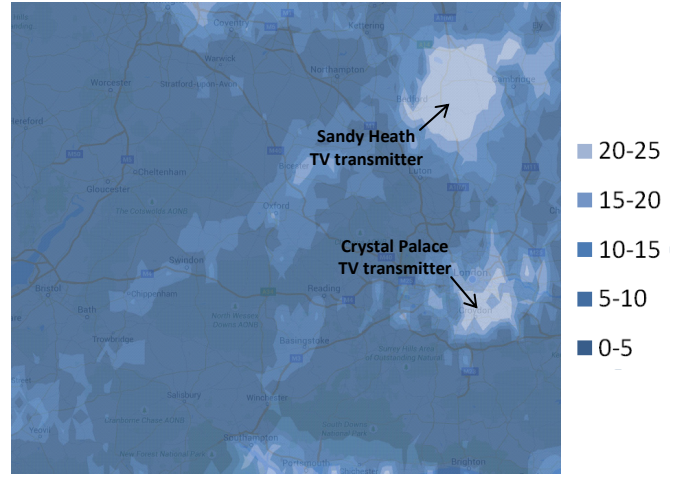
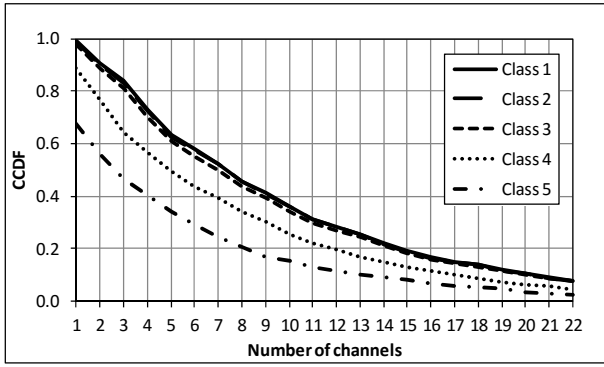


Fig. 13. Number of “usable” channels available for the mobile broadband downlink scenario in the wider area of England, Class 5 device.

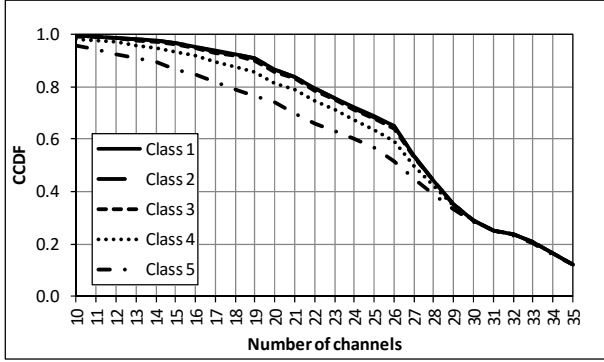
1) Expansion of Considered Area

We have succeeded in identifying a much larger area of England supported by the Ofcom framework, noting that it is challenging to extend this area as only limited locations in the UK are supported for the purpose of the Ofcom Pilot. We use this area to perform a similar assessment to Sections IV.A and IV.B, sampled at a resolution of 0.05 degrees in latitude and longitude, leading to 2,176 sampled results over the investigated area for each assessment. Fig. 12 maps this area.

The results in Figs. 13-15 reinforce our prior observations. For example, the same profound effect as for the Crystal Palace TV Transmitter arises from the Sandy Heath TV Transmitter, whereby due to the excellent and sole coverage of that transmitter given its extremely high power (200kW EIRP per channel) only one set of multiplexes is occupied in the area, greatly increasing TVWS availability. However, there is a far greater variability in availability than in our prior assessments for the London M25 area, particularly for the mobile broadband downlink scenario which has significantly reduced availability on average. This limits the scenario's



(a)

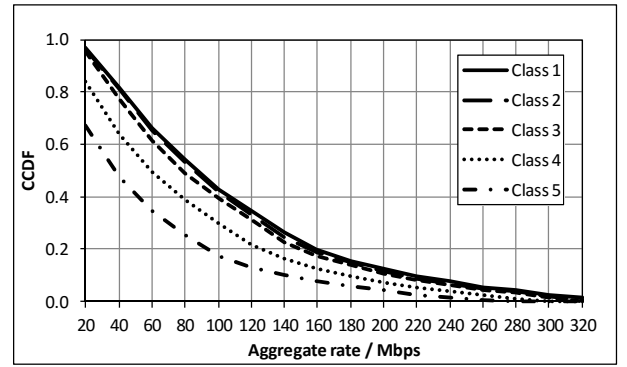


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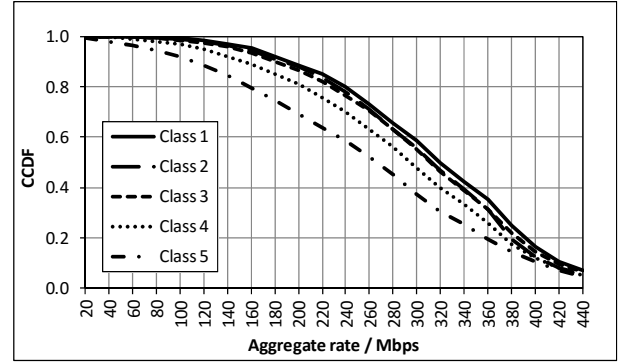
Fig. 14. CCDFs of number of available channels for the wider area of England: (a) Mobile Broadband Downlink scenario, (b) Indoor Broadband Provisioning scenario.

stability for poorer mask classes, also being reflected in the capacity that can be achieved; it is noted that to be certain of achieving white space availability at all, a Class 1-3 WSD would be necessary, noting that Classes 1-5 respectively have the following probabilities of at least 1 channel being usable under this scenario: 99.2%, 98.8%, 98.2%, 88.7%, and 67.5%. For the indoor broadband provisioning scenario, good channel availability is observed in almost all locations.

Although results are not provided here due to space constraints, we have also observed once again, for this wider area, that aggregating contiguous channels very quickly leads to the performances of the different spectrum mask classes being indistinguishable. For the Mobile Broadband Downlink scenario, aggregating only 3 or more contiguous channels makes the results generally indistinguishable. Moreover, in other work, we have shown that aggregating any number of contiguous channels under the Indoor Broadband Provisioning parameters leads to identical results (see, e.g., [21]). This observation again has profound implications for the design of WSDs. A manufacturer who wants to design a WSD under the Mobile Broadband Downlink scenario or similarly as a base station, need not be concerned with stringent spectrum mask requirements if it is aggregating 3 or more contiguous channels (only needing to satisfy Class 5). A manufacturer of indoor broadband, Wi-Fi or other such low power equipment need only design to the Class 5 specification of equipment, with virtually no gain being realised in achieving better class especially if the intention is to aggregate contiguous channels.



(a)



(b)

Fig. 15. CCDFs of achievable capacity aggregating all available channels at maximum EIRP per channel for the wider area of England: (a) Mobile Broadband Downlink scenario, (b) Indoor Broadband Provisioning scenario.

Regarding attempting to map these results to a larger area than the UK, this is not possible noting the fundamental importance of using real data from GLDBs (see Section IV.D(3)), as is done in this paper. A meaningful comparison is not possible unless other countries in Europe have implemented TVWS. This involves significant work by the regulatory administrations therein, and can not be done or convincingly predicted within the scope of research alone.

2) Expansion of Considered Scenarios

Next we assess other scenarios and deployment topologies through discussion of the differences compared with those that we have covered in this paper, and discussion of the effects of parameter changes. First, considering the *mobile broadband uplink*, transmission power will be reduced to around 20 dBm in this case and other WSD parameters will be similar to the case of indoor broadband provisioning. So, there will be excellent and much more consistent channel availability/EIRPs than there is for the downlink—in line with the indoor broadband provisioning case. However, receive SINR will be significantly affected by the interference characteristics that have been observed in this paper, and will be unpredictable on a per-channel/location basis. As has been observed, the receive SINR in such cases high above rooftops can be lowered potentially by three orders of magnitude.

Lowering the receiver slightly below rooftop very quickly leads to a situation where such inbound interference is greatly reduced. Moreover, lowering transmitters leads to vastly more white space being available—even then maintaining the high

minimum required transmission EIRP of 30 dBm. For a Class 3 WSD, for example, lowering the WSD to a height of 30m to 10m above ground level leads to an increase in the average number of channels available from 8.6 to 13.0 and a decrease in the CoV from 0.83 to 0.60. Lowering the WSD to a height of 5m gives a further increase in the average number of channels available to 19.1 and a decrease in the CoV to 0.40. Considering a scenario that needs at least 20 MHz (requiring 3 channels) for transmission, equivalent to upper-level LTE performances without aggregation, lowering the antenna to 10 m increases the percentage of locations that have at least 20 MHz available from 81.6% to 94.1%, and lowering further to 5 m increases it further to 99.2%. This indicates that scenarios where the WSDs are placed lower, e.g., on lamp posts or even on roofs of relatively smaller buildings, clearly are highly viable. However, of course propagation would not carry as well due to the significantly increased shadowing. Moreover, such deployment cases still do not lend well for long distance point-to-point links.

3) Literature Comparison

Finally, it is noted that there is typically a discrepancy between the work done here, and past work of the literature that has admirably attempted to predict TVWS availability without having access to the actual regulatory-approved database implementations and modelling. Comparing this paper with the projections for the UK in [14], [17], [19], for example, the geographical locations of TVWS availabilities in these references bear limited relation to those reported in our paper. Quoted statistics are also quite different. It is therefore clear that the best efforts of the literature in undertaking the challenging task of predicting TVWS availability are not sufficient, and assessment based on real operational regulatory GLDBs and models is necessary. The underlying reasoning for this is that the complexity of the regulatory modelling and implementation, and the number of aspects considered, is significantly in advance of those that research predictions can consider or even know about (see, e.g., [22]). It is simply not possible to second-guess the regulator.

Regarding the scenarios assessed in the literature, it is noted that scenarios such as Wi-Fi in TVWS are often projected as being successful (see, e.g., [13], [14]). We equally observe the success of such scenarios in this paper. However, we note that use of TVWS in the UK for, e.g., rural broadband provisioning (as in, e.g., [14]), is far more challenging.

V. ACT V: “CONCLUSION, AND IMPORTANT FUTURE-PROOFING OBSERVATIONS”

The Ofcom TV White Spaces (TVWS) Pilot represents an important milestone in the realization of TVWS technology. This paper has described a subset of the work of our trial under this pilot, leading an extensive consortium. It has detailed some obtained results, concentrating very extensively on the availability and capacity that is achieved in TVWS scenarios termed as “mobile broadband downlink” and “indoor broadband provisioning”, derived particularly from our observations on some of the most useful scenarios for TVWS, although also expanding to general discussion of other scenarios/topologies. Another key emphasis is on what can be achieved by aggregating resources in TVWS, and analysis of some basic means for aggregating resource.

Importantly, Ofcom has in February 2015 issued a statement approving of TVWS usage in the UK by license-exempt devices operating under the developed geolocation database-based framework [23]. However, that same statement outlined some refinements to the framework, which for the most part can be read as a tightening up of protection for incumbent DTT and PMSE services. At the time of preparing the revised version of this paper, a number of operators of the new “adjusted” databases have been qualified (approved) by Ofcom, and we have done some early work in assessing performances under these new databases. We have noted that the rules indeed lead to somewhat of a reduction in the allowed EIRPs of white space devices in channels. Nevertheless, the broad observations provided in this paper on TVWS usage and characteristics/prospects remain the same. Moreover, it is noted that in adopting these higher protection levels for the roll-out of license-exempt white space devices, Ofcom is deliberately being extremely conservative. It is our understanding that Ofcom is further planning to adapt such assumptions (likely progressively reducing their severity—to something closer to the conditions when the work was done in this paper) as long as interference is not occurring in the commercial roll-out of white space technology and devices, and also to improve the situation through better modelling of aspects such as propagation, allowing increased EIRPs.

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